

# GRAPHENE DEVICE, METHOD OF INVESTIGATING GRAPHENE, AND METHOD OF OPERATING GRAPHENE DEVICE

## RELATED APPLICATIONS

**[0001]** The application claims priority to U.S. Provisional Patent Application Ser. No. 61/183,538, filed Jun. 2, 2009, which is herein incorporated by reference in its entirety.

## STATEMENT OF GOVERNMENT SUPPORT

**[0002]** This invention was made with government support under Contract No. DE-AC02-05CH11231 awarded by the U.S. Department of Energy. The government has certain rights in this invention.

## BACKGROUND OF THE INVENTION

**[0003]** The present invention relates to the field of graphene and, more particularly, to the field of graphene devices.

**[0004]** The electronic bandgap is an intrinsic property of semiconductors and insulators that largely determines their transport and optical properties. As such, it has a central role in modern device physics and technology and governs the operation of semiconductor devices such as p-n junctions, transistors, photodiodes and lasers (ref. 1). A tunable bandgap would be highly desirable because it would allow great flexibility in design and optimization of such devices, in particular if it could be tuned by applying a variable external electric field. However, in conventional materials, the bandgap is fixed by their crystalline structure, preventing such bandgap control.

**[0005]** Graphene's unique electronic band structure has led to fascinating phenomena, exemplified by massless Dirac fermion physics (refs. 10-12) and an anomalous quantum Hall effect (refs. 13-16). With one more graphene layer added, bilayer graphene has an entirely different (and equally interesting) band structure. Most notably, the inversion symmetric AB-stacked bilayer graphene is a zero-bandgap semiconductor in its pristine form. But a non-zero bandgap can be induced by breaking the inversion symmetric of the two layers. Indeed, a bandgap has been observed in a one-side chemically doped epitaxial graphene bilayer (refs. 6,8).

**[0006]** Of particular importance, however, is the potential of a continuously tunable bandgap through an electrical field applied perpendicularly to the sample (refs. 17-20). Such control has proven elusive. Electrical transport measurements on dual-gated bilayer graphene exhibit insulating behavior only at temperatures below 1 kelvin (ref. 2), suggesting a bandgap value much lower than theoretical predictions (refs. 17,18). Optical studies of bilayers have so far been limited to samples with a single electrical gate (refs. 4,5,9), in which carrier doping effects dominate and obscure the signatures of a gate-induced bandgap. Such lack of experimental evidence has cast doubt on the possibility of achieving gate controlled bandgaps in graphene bilayers (ref. 9).

## SUMMARY OF THE INVENTION

**[0007]** Embodiments of the present invention include a graphene device, a method of investigating semiconductor properties of graphene, and a method of operating a bilayer graphene device. An embodiment of a graphene device of the present invention includes a first gate structure, a second gate structure, and bilayer graphene coupled to the first and second

gate structures. The second gate structure is transparent or semi-transparent. The bilayer graphene is situated at least partially between the first and second gate structures.

**[0008]** An embodiment of a method of investigating semiconductor properties of bilayer graphene includes providing a bilayer graphene device. The bilayer graphene device includes a first gate structure, a second gate structure that is transparent or semi-transparent, and bilayer graphene coupled to the first and second gate structures. The bilayer graphene is situated at least partially between the first and second gate structures. The method further includes probing the semiconductor properties of the bilayer graphene device using a light source to illuminate the bilayer graphene at least partially through the second gate structure.

**[0009]** An embodiment of a method of operating a graphene device includes providing a bilayer graphene device. The device includes a first gate structure, a second gate structure, and bilayer graphene coupled to the first and second gate structures. The bilayer graphene is situated at least partially between the first and second gate structures. The method further includes producing a bandgap of at least 50 mV within the bilayer graphene. The bandgap is produced by applying first and second electric fields to the bilayer graphene using the first and second gate structures, respectively.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** The present invention is described with respect to particular exemplary embodiments thereof and reference is accordingly made to the drawings in which:

**[0011]** FIG. 1: Dual-gated bilayer graphene. a. Optical microscopy image of the bilayer device (top view). b. Illustration of a cross-sectional side view of the gated device. c. Sketch showing how gating of the bilayer induces top ( $D_t$ ) and bottom electrical displacement fields ( $D_b$ ). d. Left: Electronic structure of a pristine bilayer has zero bandgap. Right: Upon gating, the displacement fields induces a non-zero bandgap ( $\Delta$ ) and a shift of the Fermi energy ( $E_F$ ). e. Graphene electrical resistance as a function of top gate voltage ( $V_t$ ) at different fixed bottom gate voltages ( $V_b$ ). The traces are taken with a 20 V steps in  $V_b$  from 60 V to -100 V and at  $V_b = -130$  V. The resistance peak in each curve corresponds to the CNP ( $\delta D = 0$ ) for a given bottom gate voltage. f. The linear relation between top and bottom gate voltages that results in bilayer CNPs.

**[0012]** FIG. 2: Bilayer energy gap opening at strong electrical gating. a. Allowed optical transitions between different subbands of a graphene bilayer. Curves are offset from zero for clarity. b. Gate-induced absorption spectra at CNP for different applied displacement fields  $\bar{D}$  (with spectrum for zero-bandgap CNP subtracted as reference). For clarity, the traces were displaced by 2%, 4%, 6% and 8%, respectively. Absorption peaks due to transitions I at gate-induced bandgaps are apparent (dashed black lines are guides to the eye). At the same time, a reduction of absorption below the bandgap is expected. This reduction is clearly observed in the trace with the largest bandgap ( $\Delta = 250$  meV) in our experimental spectral range. The sharp asymmetric resonance observed near 200 meV is due to Fano resonance of the zone center G-mode phonon with the continuum electronic transitions. The broad feature around 400 meV is due to electronic transitions II, III, IV and V. c. Theoretical prediction of the gate-induced absorption spectra based on a tight-binding model where the bandgap value is taken as an adjustable parameter.